Justification of Reconnaissance Traceability Matrix:

Europa Clipper Project Reconnaissance Working Group report

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This report was requested by the Europa Clipper Project Systems Engineer (PSE),to provide justification for the measurements described in the Europa Clipper Reconnaissance Traceability Matrix. Some of the material included in this report was adapted from an earlier report generated by the Reconnaissance Subgroup of the Europa Clipper Science Definition Team, which is included as Appendix A.

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1. Introduction

To address fundamental scientific questions regarding the habitability and composition of Europa's subcrustal ocean, a landed spacecraft capable of *in-situ* sampling and analysis represents a likely future step. To maximize success of such a landed mission, ensuring both safe landing and access to surface material of highest scientific value, some level of reconnaissance is necessary. Including a reconnaissance remote-sensing package on the proposed Europa Clipper mission may present the most effective way of obtaining this needed data.

The prospect of a future soft landing on the surface of Europa would create science opportunities that could not be achieved through flyby or orbital remote sensing, and which have direct relevance to Europa's potential habitability. Understanding Europa's habitability is intimately tied to understanding what are commonly referred to as the three ingredients for life: water, chemistry, and energy. All of these could be well addressed by a landed mission to Europa, albeit at one location. Measurements obtained from Europa's surface would provide direct analysis of the satellite's chemistry and mineralogy through *in-situ* investigations and measurements that are not possible to achieve remotely. Most important, a properly equipped lander could sample beneath the radiation-processed uppermost portion of Europa's icy shell, providing insights about its native composition and implications for life. A lander also provides an excellent platform from which to perform geophysical measurements to probe Europa's ice shell and subsurface ocean. Moreover, a landed mission could permit analyses of local surface geology at a scale inaccessible from space. Further information about the science goals of a Europa lander can be found in Pappalardo et al. (2013).

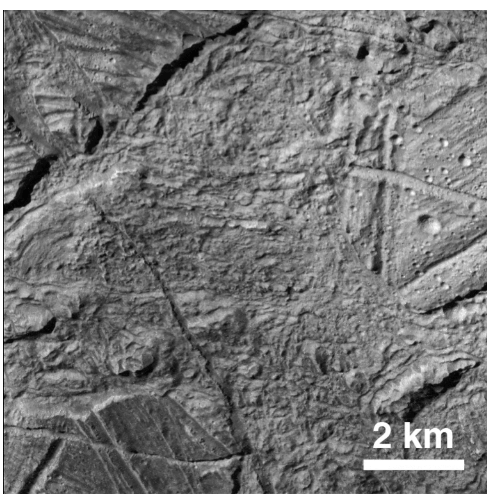

Figure 1: Only a tiny fraction of Europa's surface has been imaged at high resolutions (6-12 m/pixel). This image of part of the Conamara Chaos region shows the heterogeneity of the surface at small

The greatest uncertainty facing *in-situ* investigations on Europa's surface is the lack of knowledge as to the nature of the landscape at scales smaller than a decameter (Figure 1). This uncertainty has both substantial scientific and engineering-operational implications (Europa Study Team report, 2012), and was a key reason why a landed mission was the lowest priority mission concept to emerge from the 2012 Europa study phase. Many potential high-science-interest targets, such as chaos terrain, have a substantial likelihood of extreme roughness at the decameter to decimeter scales (e.g., Fig. 1).

The rationales for obtaining reconnaissance data are therefore two-fold. The first is to obtain sufficient information about the surface hazards and scientific characteristics at specific features of interest, from which the selection of landing-site options could be made. The second reason is to provide information about the nature of the Europan surface so as to be able to design a landed spacecraft, optimize a scientific payload, and develop a mission profile. Without realizing both of these aims, a landed mission would likely incur an unacceptably high risk. The Europa Clipper would be able to carry payload instruments specifically designed to reduce the risk to a future landed mission.

1.1 Safety and surface characteristics of potential landing sites

The highest resolution images of Europa's surface currently available are the handful acquired by the Galileo spacecraft with resolutions that range from 6–12 m/pixel. These show a surface that is rough down to the pixel level, containing fractures, slopes, and scarps. Most daunting are plates and matrix material resulting from chaos formation (Figure 1), although these are scientifically very attractive places to explore. Imaging of very young and active terrain on Saturn's satellite Enceladus at resolutions of 4 m/pixel reveals a landscape with many large ice boulders (Figure 2).

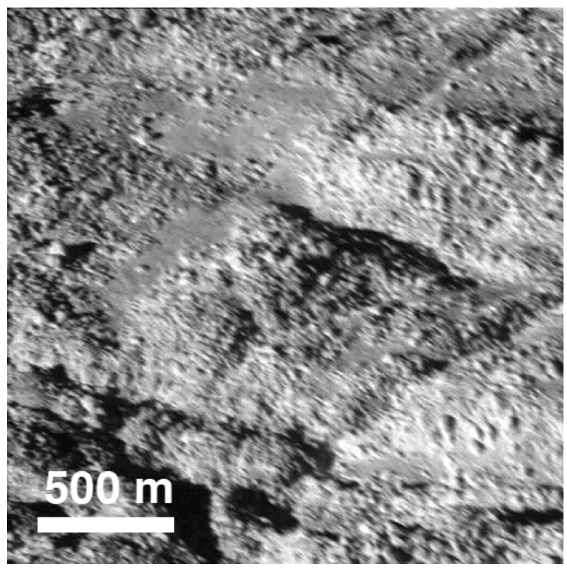

Figure 2: The surface of Enceladus, imaged by Cassini at 4m/pixel, shows a predominantly rough texture with numerous boulders.

It is impossible to be certain of the character of Europa's surface at lander scales without additional data of multiple candidate landing sites, which would need to be obtained either prior to a lander mission or concurrent with it (preceding lander release, however the Europa lander study showed that this approach has high risk). Based on existing slope and imaging data, we can expect that Europa's surface may be rough at small scales, even in places that appear smooth at larger scale (10s to 100s m/pixel).

1.2 Scientific merit of potential landing sites

A lander mission will want to sample materials that are relatively young and pristine, and are derived from Europa's interior. The compositions of Europa's surface and near-surface materials are expected to vary with the amount of exposure to Jupiter's radiation environment (e.g., Patterson et al. 2012 and references therein). The lower latitudes of Europa's trailing hemisphere will be radiolytically processed to depths of at least several centimeters and may be processed at up to meter depths. However, the leading hemisphere of the satellite, and higher latitude regions of the trailing hemisphere, may only be affected to depths in the micron to centimeter range. Although the average age of the surface is relatively young (~60 Ma, Schenk et al. 2004), stratigraphic mapping has shown that Europa's landforms are of different relative age (e.g., Greeley et al. 2004), and certain classes of feature—specifically chaos features—appear to be among the youngest landforms on the surface so are probably less radiolytically processed.

Revealed by cross-cutting relationships, most geological features appear to have a low albedo when newly formed, then to gradually brighten with age, ultimately reaching a relatively uniform high-albedo brightness. Although the exact mechanism for this process is not well understood, it is likely related to radiation processing and/or the deposition of frost (e.g., Geissler et al. 1998). This brightening correlates with relative age, such that the youngest features on the surface are typically the darkest, while intermediate-aged features appear to be gray, and the oldest features are bright and largely indistinguishable in brightness from each other (e.g., Prockter et al. 2002). Shirley et al. (2010) used spectral data from the Galileo NIMS instrument to show that there is a distinct gradient in composition across the leading-trailing hemisphere boundary, verifying suspicions that the composition of surface units is altered by radiation processing (Carlson et al. 2009 and references within). Thus, the most promising compositional targets for a landed mission are the youngest, least radiation-processed materials, which also tend to be the lowest in albedo.

Chaos regions and smooth plains deposits within lenticulae appear to have generally disrupted and/or embayed the preexisting terrain, implying that they are relatively young, and that they at least partially consist of material that has been brought up from the subsurface (e.g., Greeley et al., 2004). Thought to have formed from diapiric upwellings (e.g., Collins and Nimmo, 2010 and references therein), these features may have entrained subsurface material, and the briny deposits associated with chaos may represent subsurface ocean water or lenses of water (Schmidt et al. 2011). Thus chaos regions, especially those associated with smooth, dark plains deposits, are of particular interest for compositional measurements.

2. Reconnaissance traceability matrix background and justification

The reconnaissance effort has one overarching goal: "**Characterize Scientifically Compelling Sites, and Hazards, for a Potential Future Landed Mission to Europa**," which is divided into two major objectives. The first involves characterizing the safety of landing sites on Europa to ensure that any spacecraft can land safely and be adequately supported after touchdown. The investigations that follow on from this objective are relevant to the roughness of the surface at a variety of scales that could affect a safe landing, including surface slopes, cracks and boulder distribution, and any loose material on the surface that could impede adequate stability on and contact with the surface. The second objective is designed to ensure that any landing site on Europa is acceptable from a scientific standpoint, given the cost and resources that would be required for a landed mission. The investigations that follow on from this objective are relevant to the nature of the surface materials, and how and when they were emplaced onto the surface, so that a lander would have the best possible chance of measuring recently emplaced and therefore fresh (i.e., with little radiation-processing) material available.

A Reconnaissance Traceability Matrix (hereafter referred to as the RTM) has been constructed by the Science Definition Team (http://solarsystem.nasa.gov/europa/sdt2013.cfm), which shows the flowdown from goal to objectives, investigations, and measurements, and identifies candidate instruments that could meet each objective. The scientific goal for reconnaissance is specifically separated from the primary science goals of the Clipper mission (see 2012 study report Science Traceability Matrix), because it is not specifically a science priority, and instead has a programmatic purpose.

We here step through each of the investigations in the RTM, in order to provide explicit justification for the choices and reasoning that led to them.

2.1 SC.Characterize the surface properties of potential landing sites on Europa

The main requirement for engineering safety encompasses the single objective: *Assess the distribution of surface hazards, the load-bearing capacity of the surface, the structure of the subsurface, and the regolith thickness of at least 15 sites of interest for a future landed mission*.

Based on experience with other planetary landed missions, a Europa lander would need to be able to stably land on slopes of up to ~25 degrees on a three-meter baseline and manage surface obstacles (ice blocks, hard protrusions, and other roughness characteristics) extending up to one meter above the surface. Europa's surface is dominated by an unknown combination of tectonic, cryovolcanic, mechanical, space weathering, and sublimation processes. In addition to slopes and blocks, roughness elements could potentially include scarps, steps, cracks, divots, cusps, and spires.

Imaging is key to meeting this landing safety objective. Images can reveal surface block size populations, roughness elements (pits, cusps, etc.), and areal distributions through cast shadows. High-resolution imaging is also needed to understand lander-scale and landing-ellipse-scale geological variability, surface age and resurfacing history, resurfacing mechanisms, and physical weathering processes. High-resolution stereo imaging is necessary to characterize surface slopes as a landing hazard. In addition, stereo data is valuable in understanding regolith movement (slope stability) and cohesion, tectonic uplift and subsidence, cryovolcanic flow thickness, and surface degradation rates relative to impact rates and surface age. Stereo-pair observations require similar lighting conditions (if not the same), necessitating paired images on the same flyby pass or careful timing and alignment of different flyby passes.

Observations of brightness temperature of the surface can be used to estimate regolith particle cohesion, block abundance, and bedrock exposures. Observations at more than one time during an orbital cycle (i.e., diurnal variation) can additionally aid in interpreting regolith thickness and subsurface cohesion. The objective of engineering safety is met with four investigations, each of which encompasses 1-2 measurements.

2.1.1. Investigation SC.1: Determine the distribution of blocks and other roughness elements within a potential landing site at scales that represent a hazard to landing.

The surface of Europa has not been imaged at resolutions of better than 6 m/pixel, and even those data are obtained with oblique viewing geometry and only cover a few tens of square kilometers of the surface. Landed missions to other planets (e.g., Mars, Venus, Titan, the Moon) have found evidence of blocks on the surface, resulting largely from water-borne, aeolian, impact, volcanic, or mass wasting processes. Europa's surface is relatively young, only ~60 Ma on average, thus it is not expected to have developed a significant regolith as a result of impact cratering. However, it does show evidence of significant tectonic activity, with cracks and ridges at all angles on the surface and at all scales resolved to date. The creation of these features and mass wasting from their slopes is expected to have produced numerous blocks on the surface, perhaps like those on the surface of Enceladus (Fig. 2). Because such blocks could prove to be a considerable hazard to a landed spacecraft, Clipper reconnaissance would determine the number of blocks and their distribution in selected areas of interest. These measurements could then be extrapolated to other potential areas of interest for future landed missions.

Figure 3: Penitentes, ice spires that form under particular circumstances at high latitudes on Earth (Top: unknown author; Bottom: Peruvian pentitentes, credit: Luis Buignon).

Based on terrestrial experience, recent modeling of sublimation-driven ice features suggests that in equatorial Europan latitudes, penitente ice blades (Fig. 3) may form with depths ranging from 10 cm to as much as 10 meters (Hobley et al., 2013), and spacing about half of this. Further to the north and south, the surface is expected to be smoother due to the dominance of diffusive sputtering erosion. Understanding the production and distribution of non-boulder features such as these is crucial to characterizing safe landing locations.

Measurement SC.1a: **Measure the occurrence of blocks protruding 1 m and more above the surface, and the abundance and nature of surface roughness elements at scales as small as 1 m.**

The floor for this measurement is that data will be collected from least 15 sites of expected geological diversity and interest for a future landed mission, based on existing data and, if necessary, extrapolation to previously unimaged areas. Historical attrition rates of Mars potential landing sites suggest that approximately 1 in 10 sites will be certified as offering acceptable risk and appropriate science. Given the unknown basic nature of Europa's surface at the lander scale (relative to the volume of knowledge of Mars' surface), balanced by the absence of a substantial atmosphere and associated uncertainties, we estimate an attrition rate between 7:1 and 8:1 may be appropriate for down-selecting potential Europa landing sites. Therefore, we estimate that at least 15 sites will need to be fully investigated (observed with a full complement of reconnaissance instruments) in order to certify at least two minimal-risk site options for a future landed mission. These sites should also represent a range of geological diversity in order to avoid lander-scale hazards that may pathologically occur for certain types of terrains. Investigating more than a minimum of 15 sites, Clipper baseline of 40 sites, provides robustness, given the current nearly complete lack of knowledge of surface structure or the geological and geophysical process that mold the surface at the scale of a lander.

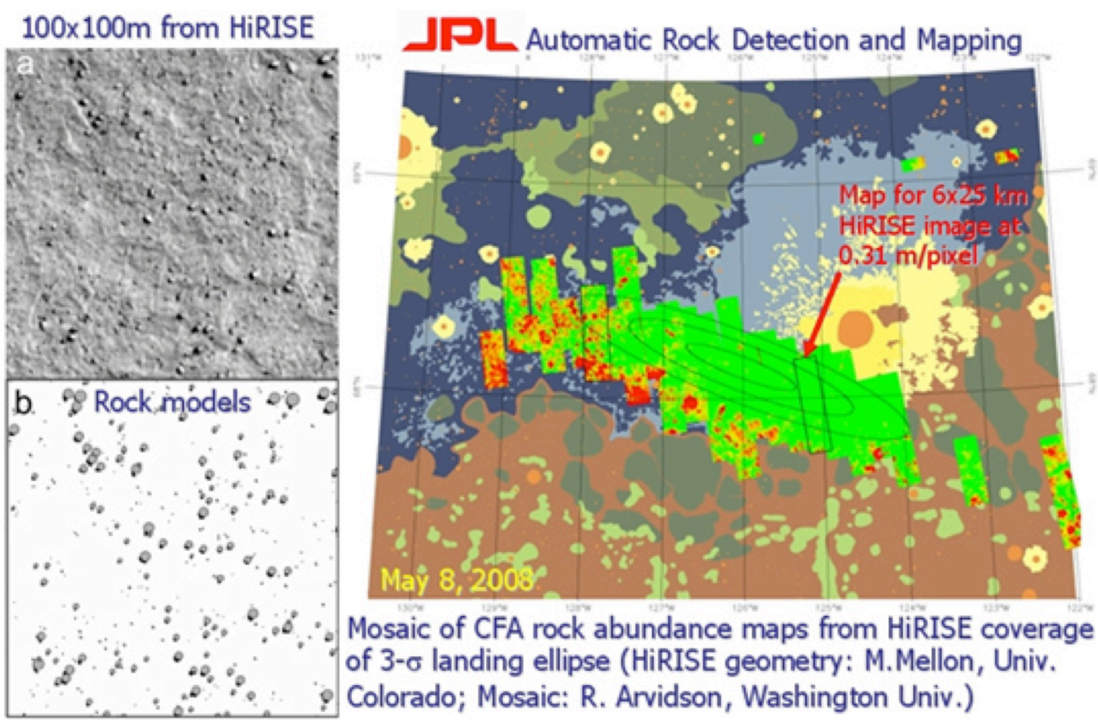

Figure 4: Example of how rock abundance maps were generated from HiRISE 0.3 m/pixel images in order to determine the Phoenix landing ellipse (NASA/JPL).

The areal coverage required for each site of interest is at least an ellipse of 2x10 km (floor), but the measurement baseline is to image an ellipse 2 or more times that size (5x10) in order to optimize the chance of finding a safe location to land within a given area.

In order to gauge block distribution and size, a candidate landing site needs to be imaged at solar incidence angles sufficient that distinct shadows can be measured from the blocks, allowing their heights to be estimated (Fig. 4), or digital elevation models need to be extracted from stereo images. How well this can be done depends on the resolution of the image (e.g., plate scale and point spread function, PSF) as well as the viewing and lighting geometry. The nominal image resolution results from a balance between incidence angle (dictating the scale of the shadow cast) and the desired block height to be detected. The baseline incidence angles for the approach of measuring shadows are between 45 and 70º. Higher incidence angles risk completely shadowing sloped surfaces leaving gaps in the reconnaissance coverage. Lower incidence angles will necessitate high resolution images, and rapidly degrade the ability to detect blocks smaller than 1 m. However, near zero incidence would cast no shadows. In this nominal range of 45º and 70º a resolution equal to or better than 0.5 m/pixel would be needed.

Monochromatic imaging is sufficient for this measurement, although color imaging could potentially be helpful in interpreting compositional variability (this has not yet been demonstrated from existing data). The 0.5 m/pixel scale assumes a signal-to-noise ratio (SNR) of at least 100:1 in order to provide good visual interpretation of the local morphology, along with optimal PSF and spacecraft jitter. Finer resolution imaging is strongly desired. If images are acquired at better than 50 cm/pixel, they could be useful for detecting the occurrence and nature of roughness elements that might interfere with sampling from a future lander, but this is not a requirement. To understand the relationship between high-resolution imaging and the regional-scale and global-scale geologic history, context imaging is needed to bridge resolution gaps. Depending on the terrain, resolution steps of 10x or lower are needed to transition between resolutions.

Measurement SC.1b: Characterize the fractional area of block coverage and the areal distribution of roughness elements by measuring the contrast in thermal emission between at least 2 spectral channels at local times of day between 10 AM and 3 PM and at a spatial resolution on the surface of better than or equal to 250 m/pixel.

. Visible measurements of the size and distribution of blocks and roughness elements (cracks, spires, etc.) across a candidate landing site used in concert with thermal infrared observations provides a robust characterization of surface hazards. Thermal infrared observations allow confirmation of the interpretation of visible rocks, determination of block abundance and bedrock exposures and extrapolation across size ranges, as well as crucial physical interpretation of the surface material (solid, particulate, etc). Surface bolometric albedo observations are required in order to model temperature – without albedo measurements the thermal measurement and subsequent interpretations are less accurate and requires many more observations over multiple times of day.

Such observations can be acquired with a thermal imager using at least two spectral channels with minimal overlap between them. At most times of day, thermal contrast occurs between solid blocks and particulate regolith, and these measurements allow the derivation of a block fraction and regolith thermal inertia. These measurements are model dependent but have been extensively used at Mars since the 1980s, and have proved somewhat accurate and valuable (e.g., Golombek et al., 2003). These measurements will be most sensitive to blocks larger than a diurnal skin depth (about 45 cm for ice blocks on Europa).

As far as is possible, thermal measurements should be spatially coincident with imaging from the reconnaissance imager in order to interpret the physical characteristics of any blocks. Ideally the measurements should be made between 10 am and 3 pm in local time; measurements outside of this range can cause ambiguous results that cannot be adequately interpreted. The measurements need to cover the same baseline and floor landing ellipses as in measurement SC.1a, and the required resolution for the thermal imager is 250 m/pixel or better, which would adequately resolve landforms of interest. Bolometric albedo measurements should be made in order to facilitate accurate reduction of temperature data. Based on Mars-TES experience, albedo measurements should be between 0.3-3 micrometers, with a baseline <0.005 accuracy, or a floor accuracy of 0.01. Over the full temperature range of 90-130K, the noise equivalent temperature uncertainty (NEDT) should be less than or equal to 0.5K in each channel, also based on the Mars-TES experience.

2.1.2 Investigation SC.2: Determine the distribution of slopes within a potential landing site over baselines relevant to a lander.

Even if there are no blocks or other roughness elements present on a surface, a landed spacecraft must be able to land and remain stable, driving a requirement for low slopes. High-resolution stereo imaging is necessary to characterize surface slopes as a landing hazard, and to place requirements on future terrain-relative navigation.

Topographic data derived using stereo and photoclinometric analysis of Galileo images has been used to derive Europa's general slope characteristics. Schenk (2009) shows that slopes for major terrain types - ridged plains, chaos matrix and crater deposits – are typically between 10° and 15° at 10-100-m length scales. The smoothest terrains found in his analysis are smooth bands, which have RMS slopes of ~5°, but other than these, almost no smooth areas larger than a few kilometers across occur on Europa.

Measurement SC.2a: Measure surface slopes of up to 25° on a 3 m baseline for all azimuths by acquiring stereo paired images with a spatial resolution of better than or equal to 0.75 m/pixel.

The goal of measuring surface slopes of up to 25º on a 3-m baseline comes from experience in other landed missions and the necessary footprint size needed to safely contain a landed spacecraft. Stereo-pair observations require similar lighting conditions (if not the same), necessitating paired images on the same flyby pass or careful timing and alignment of different flyby passes. Incidence angles of between 20º and 70º (baseline) are sufficient, but the second half of the stereo pair should have essentially the same incidence angle as the first. Incidence angles of greater than 70º result in shadowing that is comparable to the slopes of interest, so is highly undesirable as it would leave to substantial gaps in the surface coverage. The required stereo convergence angles are between 15° and 30º, based on other planetary stereo data. Monochromatic imaging is adequate for this measurement, with SNR greater than or equal to 100, over the baseline landing ellipse of 5x10 km (2x10 km floor). Spacecraft pointing uncertainty must be known such that there is at least 90% overlap with the stereo pairs in both cross-track and down-track directions.

Measurement SC.2b: Characterize the statistical distribution of slopes from nadir track altimetric information having a relative height accuracy of 1 m.

The Ice-Penetrating Radar (IPR) instrument that is a floor science instrument in the model payload of the Clipper can be utilized to understand the surface slopes. This measurement utilizes IPR data collected in support of science traceability matrix investigations to complement the reconnaissance imager in determining the parameterized statistical distribution of slopes at a potential landing site (SC.2a). The IPR model instrument acquires nadir profiles of the surface and subsurface for flyby altitudes less than 1000 km at frequencies of 60 and 9 MHz and for bandwidths of 10 and 1 MHz. The single-pulse range-resolution of each frequency and bandwidth is 15 m and 100 m. The requirements of this measurement are satisfied by parameterizing the scattering function at these frequencies using the

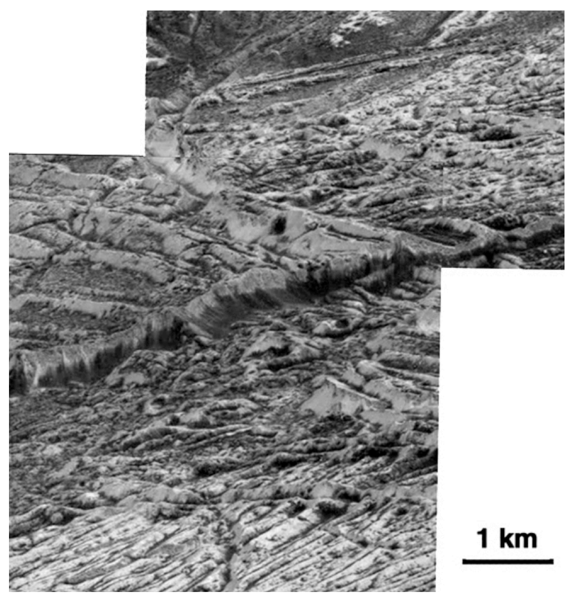

Figure 5: Some high-resolution images of Europa show evidence of mass wasting down slopes (e.g., dark material along prominent scarp running through the center of this 12 m/pixel Galileo image). It is possible that such landscape erosion is also prominent at decimeter or centimeter scales.

differences in echo energy between looks (or across different focusing windows) to measure the statistical distribution of slopes (Schroeder et al., 2012). Understanding the statistical distribution of slopes at the scale of a lander is useful for characterizing the safety of potential landing sites and comes at no additional cost to spacecraft resources. If available, IPR profiles would provide supportive evidence with which to compare with stereo-imaging-based slope data acquired for measurement SC.2a. An IPR profile is only desired through a portion of the baseline landing ellipse coverage, in order to coordinate observations, rather than the entire area.

2.1.3. Investigation SC.3: Characterize the regolith cohesiveness and slope stability within a potential landing site.

In order for a landed spacecraft to operate on the surface, it must be stable after landing. In addition, sampling and other scientific measurements of the surface require knowledge of structure of the surface layer. Thus an understanding of the extent and characteristics of the regolith in the candidate landing sites is required, which can then be tied to slope information. Knowledge of the regolith structure would place additional constraints on the rate of formation, ablation, and gardening of surface materials being chemically analyzed. Thermal inertia alone combines cohesion, rockiness, and subsurface layering into one parameter, which are difficult to separate without additional data such as high-resolution imaging and temperature as a function of time of day. Such a combination of datasets was used at the Phoenix landing site to accurately assess the depth of ground ice in site assessment (Spencer et al., 2009), and such data could be acquired by the Clipper. Europa's surface shows evidence of mass wasting of material downslope, along scarps that are several hundred meters in height (Fig. 5). Reconnaissance would investigate the characteristics of Europa's regolith at small scales.

Measurement SC.3a: Determine the regolith-component thermal inertia (distinct from blocks) of the upper decimeter-scale surface layer by measuring the contrast in thermal emission between at least 2 spectral channels at local times of day between 10 AM and 3 PM and at a spatial resolution on the surface of better than or equal to 250 m/pixel. Require sufficient albedo accuracy to facilitate accurate reduction of temperature data.

Thermal observations can be used in a variety of ways to constrain the thermal inertia of the regolith within a candidate landing ellipse (including such structural properties as particle size, porosity, density, ice-grain sintering) through derivation of the thermal inertia of the surface layer (e.g., Spencer et al. 1999, Rathbun et al. 2010; see also Mellon et al. 2008 for discussion of thermal inertia). Combined with knowledge of slopes (SC.2), this information is important for determination of whether a slope will present a hazard to a landed spacecraft. The measurement requirements for understanding the thermal inertia of the regolith component of the surface are the same as for SC.1b.

Measurement SC.3b: Identify small scale landforms associated with mass movement from monochromatic stereo image data at a spatial resolution on the surface of better than or equal to 0.5 m/pixel.

Small-scale mass wasting can provide information about the age and mechanical properties of a surface, providing information about its stability. For this measurement, stereo data is valuable in understanding regolith movement (slope stability) and cohesion, tectonic uplift and subsidence, cryovolcanic flow thickness, and surface degradation rates relative to impact rates and surface age. The requirements for this measurement are the same as those for SC.1a, and would enable the discrimination of features showing evidence of mass movement, among other types of surface morphology.

2.1.4 Investigation SC.4: Determine the regolith thickness and whether subsurface layering is present within a potential landing site.

This investigation has similarities to SC.3, but is instead focused on understanding the very-near-surface characteristics of candidate landing sites. Regoliths form by a combination of processes on airless bodies, the most dominant being impacts. Europa's surface is relatively young and sparsely cratered and is therefore not expected to have a well developed regolith such as is inferred on other Galilean satellites such as Callisto and Ganymede [Moore *et al*., 2009]. However, micrometeorite bombardment along with the constant flux of high-energy particles and sublimation erosion may have allowed a surface regolith layer to form perhaps on the order of centimeters to meters. This depth would be expected to be deeper in older areas of the surface, and scant in the youngest regions. Knowledge of the presence of and depth of regolith on Europa's surface is a key component in understanding the safety of landing sites and for engineering sampling and analysis methods.

The highest resolution Galileo images of Europa showed hints of layering within some of Europa's ubiquitous double ridges (Fig. 6), exposed by later tectonic activity. The observed layering indicates potential mechanical or compositional differences beneath the surface of the ridges. Understanding the extent, depth and distribution of such layering will be important in the design of science sampling and handling instruments. The relative depth of regolith can be investigated using thermal imaging, while a search for layers in the subsurface can be accomplished using high-resolution imaging.

Measurement SC.4a: Characterize the depth of regolith to "bedrock/ice" at the cm-scale by measuring the daytime and nighttime contrast in thermal emission between at least 2 spectral channels for a spatial resolution on the surface of better than or equal to 15 km/pixel and at local times of day between 10 AM and 3 PM and 3 AM and 6 AM. Require sufficient albedo accuracy to facilitate accurate reduction of temperature data.

For this measurement, data would be acquired at different times of day and night, in order to characterize the thermal inertia of the surface, and hence infer the regolith character and thickness. At least two spectral channels are required with sufficiently minimal spectral overlap over the landing ellipse targets, with noise equivalent differential temperature (NEDT) and albedo requirements similar to those of SC.1b. The spatial resolution of better than or equal to 15 km/pixel should be spatially, rather than temporally, coincident with reconnaissance visible imaging. The measurements need to be taken between 10 am and 3 pm and nominally between 3 am and 6 am – some must be pre-dawn, and sufficient albedo accuracy is required to facilitate accurate reduction of temperature data. These measurements are required for all candidate landing sites.

Measurement SC.4b: Identify small scale landforms associated with exposed layers from monochromatic stereo image data at a spatial resolution on the surface of better than or equal to 0.5 m/pixel.

The high-resolution imaging possible using the reconnaissance camera would enable the identification of layering within the subsurface, if such were exposed by, e.g., fracturing or mass wasting (Fig. 6). Similar layering was identified within Europa's double ridges by Galileo imaging at ~12 m/pixel, implying layers of at least that thickness. Mass wasting deposits may also originate from distinct layers in the subsurface. The requirements for this measurement are the same as those of SC.1a.

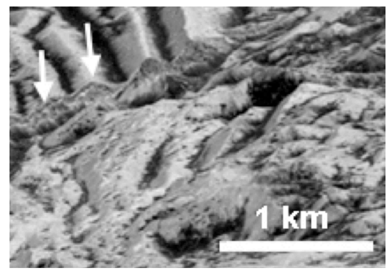

Figure 6: Galileo high-resolution images of Europa's surface show apparent layering within some double ridge crests (arrows).

2.2 SV. Characterize the scientific value of potential landing sites on Europa

The main requirement for assessing the scientific value of a Europan landing site encompasses the single objective: ***Assess the composition of surface materials, the geologic context of the surface, the potential for geologic activity, the proximity of near surface water, and the potential for active upwelling of ocean material of at least 15 sites of interest for a future landed mission.***

The scientific payload of a future lander would probably address questions of habitability through drilling, sampling, and analysis. The payload would presumably require access to relatively pristine surface materials that may lie beneath a particulate and significantly altered regolith of unknown structure and thickness. Local lander-scale variability is expected due to differences in surface age, redistribution of unconsolidated regolith, and sublimation/condensation/cementing of volatile ices. The purpose of this objective is to ensure that the candidate sites are characterized as comprehensively as possible so that informed choices can be made in choosing sites for a future landed mission. This objective would be met by 4 science investigations, each leading to 1-2 measurements.

2.2.1 Investigation SV.1: Characterize the composition and chemistry of potential landing sites with an emphasis on understanding the spatial distribution and degradation state of endogenically derived compounds.

Spectral measurements have shown that low-albedo, disrupted areas on Europa's surface are comprised of non-ice components including hydrated materials. An important objective for Europa science is to determine the compositions and origins of these hydrated materials and additional compounds; thus, these dark, disrupted features are key areas of interest for compositional measurements. To choose the best locations for compositional measurements, however, other factors must be taken into account, including the likely genesis of landforms, their relative age, degree of radiolytic weathering, and whether or not they have exchanged material with the subsurface.

Measurement SV.1a: Identify the presence of relevant endogenically derived compounds by measuring surface reflectance over the wavelength range of 850 to 5000 nm at a spatial resolution of better than or equal to 300 m/pixel.

Analysis of Galileo Near-Infrared Mapping Spectrometer (NIMS) data has revealed remarkable compositional variability among landforms located in close proximity, and has demonstrated the effects of radiation in modifying the surface. Shirley et al. (2010) showed that geographically adjacent features could have different compositions, implying that some were younger than others, and hence were more recently emplaced. Because Galileo images show that the surface is of mixed albedo in disrupted areas (e.g., Fig. 6), it is highly desirable to characterize the composition of heterogeneous areas at the highest possible resolutions, in order to determine which features are the youngest and therefore, exhibit the lowest levels of radiation weathering. Such features are expected to be the most likely to represent the composition of material from subsurface fluid reservoirs and possibly even Europa's ocean.

Adequate measurements must be obtained to interpret the composition of small-scale landforms, e.g., ridges, small chaos regions, smooth plains, etc. along with their sources and variability, as closely as possible to the scale of the lander. In order to do this, the surface reflectance should be measured over a spectral range of 850 – 5000 nm, with a spectral resolution of 10 nm in the range less than 2500 nm, and 20 nm from 2500 nm to 5000 nm (this is the same requirement as for the Clipper science objectives). The spatial resolution of these data should be better than or equal to 300 m/pixel and they should be spatially coincident with the high-resolution imaging over the candidate landing ellipses. Higher resolution spectral measurements are highly desirable.

2.2.2 Investigation SV.2: Characterize the potential for recent exposure of subsurface ice or ocean material and resurfacing vs. degradation of the surface by weathering and erosion processes and provide geological context for potential landing sites.

Given the radiation and impact processing of materials on Europa's surface, a major objective for a future landing site is to seek areas in which subsurface material - which may be derived from the ocean - has been exchanged with the surface in recent geological times. As described for SV.1, a key way to determine this is from composition; however, compositional measurements are unlikely to be at the decimeter or better scale, so some inferences will need to be made. The use of high-resolution imaging will be invaluable in determining geological relationships, especially cross-cutting relationships, which allow relative age derivations, as well as the types and extent of small-scale erosional features, which can provide information about surface processes.

Measurement SV.2a: Identify small-scale landforms diagnostic of the local geologic history of potential landing sites from monochromatic stereo image data at a spatial resolution on the surface of better than or equal to 0.5 m/pixel.

The intent of this measurement is to investigate how the surface formed at small-scales. Evidence of weathering processes involving the atmosphere or liquid has been observed in surface images of Venus, Titan, and Mars, by the Venera landers, the Huygens probe, and various Mars landers respectively. These images have provided a wealth of information as to how surface materials are eroded, transported and deposited. Images of the lunar surface have provided information about impact and regolith processes. Because Europa has no atmosphere, very few impacts, and surface deformation likely on a scale of hundreds of meters to kilometers, it is expected that only small-scale regolith processes (centimeters to meters) could be usefully studied from the surface, such as those observed on the Moon or the asteroids Eros and Itokawa (Fig. 7).

Figure 7: Images of asteroid Itokawa's surface acquired at up to 0.006 m/pxl show the boundary between rough terrain and the smoother pebble-covered Muses Sea. The location of the close-up is indicated on a global image of Itokawa (right). [JAXA]

High-resolution imaging can also aid in understanding the small-scale processes associated with Europa's major landforms (chaos regions, ridges, bands, impact craters, etc.). For example, regions of the surface that are apparently smooth at the decameter scale (e.g., Castalia Macula [Prockter and Schenk, 2005]) may be extremely rough at the sub-meter level, which could yield insight into the properties of the material that forms such units. The measurements required to meet this objective are the same as those for SC.1a.

Measurement SV.2b: Identify landforms diagnostic of the regional geologic history of the surface that include potential landing sites through imaging at a spatial resolution on the surface of better than or equal to 50 m/pixel.

The acquisition of topographic data from the surfaces of planetary bodies has revolutionized our understanding of formation processes on those bodies and their evolutionary histories. For Europa's relatively young surface, an understanding of local topography will help elucidate the relaxation state of features, enabling their ages and formation processes to be inferred. It will also aid in understanding the surface properties of ice and non-ice materials at Europan temperatures and their mass wasting characteristics.

Stereo imaging at a spatial resolution of better than or equal to 50 m/pixel (floor) will enable the topography of Europa's primary morphological features to be characterized, and will aid in the identification of smaller impact features. The topographic images will be used as context for the high-resolution imaging (5 m/pixel baseline). The area over which topographic data is acquired needs to be approximately 10x larger than that acquired for the high-resolution reconnaissance imaging, but also needs to be large enough to identify large-scale landforms. This leads to a baseline requirement of spatial coverage of a region 100 x 100 km or more, to be boresighted with the high-resolution imager. A floor requirement would be 25 x 100 km of areal coverage. The ideal incidence angle is 50º (baseline of 45° to 70°), but this could be relaxed to a floor of between 20 and 80º. SNR of 100 or more is required for best visible analysis.

2.2.3 Investigation SV.3: Characterize the potential for shallow crustal liquid water beneath or near potential landing sites.

While the availability of liquid water is perhaps the best resolved aspect of Europan habitability; nonetheless, there remain areas where this understanding can be improved. Determining the volume and depth of the ocean would provide important additional constraints on the chemical evolution of the ocean—e.g., water-to-rock ratios and pressure temperature constraints for thermodynamic and kinetic models of silicate-

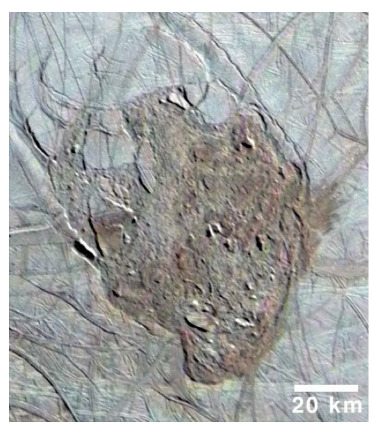

Figure 8: Thera Macula, imaged here at 220 m/pixel by Galileo, may be a region of active chaos formation above a large liquid subsurface water reservoir. Topographic data indicates that Thera lies low relative to its surroundings, suggesting the presence of liquid subsurface water today.

water interactions. Furthermore, determining the spatial distribution of liquid water within the ice shell (e.g., Schmidt et al. 2011), if any, would inform the possibility for transiently habitable regions beyond the ocean that could differ substantially in several aspects of their suitability for life. Thus, identifying candidate landing sites that are in proximity to subsurface water is a high priority for any reconnaissance effort.

Measurement SV.3a: Identify and characterize the nature of subsurface thermal or compositional horizons and structures related to the current or recent presence of water or brine within the upper 100 meters to 3 km at 10-meter or better vertical resolution.

This measurement utilizes ice-penetrating radar (IPR) data collected in support of science traceability matrix investigations to assess whether shallow bodies of water or brine are present beneath a potential landing site. Subsurface detection of shallow liquid water would raise the likelihood that surface materials may have recently cryovolcanically extruded or been tectonically uplifted. Used in conjunction with high-resolution and context imaging these data would help clarify the resurfacing history at lander and ellipse scales.

The IPR acquires nadir profiles of the surface and subsurface for flyby altitudes less than 1000 km. The vertical resolution of the measurement is required to adequately characterize the presence and magnitude of shallow bodies of water or brine and is driven by the choice of frequency (60 MHz for this implementation). This measurement is acquired during every close approach for science reasons, and therefore comes at no additional cost to spacecraft resources.

Measurement SV.3b: Acquire surface topography of better than or equal to 250-m horizontal scale and better than or equal to 20-m vertical resolution and accuracy extending a lateral distance from the ground trace sufficient to cover the width of the subsurface profiles.

Surface topography is required to enable the interpretation of the radar data, but also to investigate the slope characteristics of regions that may have been active in recent times (Fig. 8). An understanding of slopes enables discrimination of models of feature formation, which will be crucial to understanding where to land on and sample the surface. The desired topographic measurements are planned as part of the primary science data acquisition, and come at no additional cost to spacecraft resources. The width of the swath obtained by the topographic imager is dependent on the altitude at which the Clipper spacecraft flies above Europa.

2.2.4 Investigation SV.4: Characterize anomalous temperatures (that are significantly out of equilibrium with expected nominal diurnal cycles) indicative of current or recent upwelling of ocean material at or near potential landing sites.

Thermal infrared imaging can be used to locate potential “hot spots,” sites of recent or active exposure of warm subsurface or oceanic material. Models of cooling history of warm ice or cryolavas erupted onto an icy surface suggest that the detectable lifetimes of such features could be up to thousands of years. The challenges associated with observing plume activity therefore make it much more likely that active regions might be detectable by their surface thermal signatures.

The Galileo spacecraft carried a photopolarimeter-radiometer (PPR) experiment, which made over 100 observations of the surface of Europa. These were used to constrain a diurnal thermal model and thus map the thermal inertia and bolometric albedo over 20% of the surface (Rathbun et al., 2010). Results showed increased thermal inertia at mid-latitudes that did not appear to correlate with geology, albedo or other observables, and no endogenic activity was detected at Europa. However, due to the limitations of the PPR instrument and the challenges associated with making sufficient observations, it is possible that 100 km^2 hotspots with temperatures of up to 1200K could exist on the surface of Europa as yet undetected. While it is challenging to search for hotspots on Europa, the discovery of such would be of immense value to the reconnaissance effort.

Measurement SV.4a: Determine the presence of surface temperatures in excess of diurnal equilibrium indicative of active or recent extrusion, upwelling, or outgassing at each potential landing site by measuring thermal emission at local times of day between 10 AM and 3 PM and at a spatial resolution on the surface of better than or equal to 250 m/pixel.

The presence of activity, such as thermally buoyant upwelling ice, beneath Europa's surface can be determined using thermal imaging. A resolution of better than or equal to 250 m/pixel (baseline and floor) is sufficient to characterize the major surface features, especially lenticulae and chaos regions, which are generally at least a few kilometers in diameter. Measurements would be made during the day, between 10 am and 3 pm (baseline and floor), but it is desirable to make corresponding measurements at other times, especially at pre-dawn, to reduce the effects of Europa's diurnal cycle. Only one spectral channel is required for this measurement, but it should be made in regions coincident with high-resolution imaging (although not necessarily at the same time).

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Appendix A

Reconnaissance for a Future Europa Landing

Reconnaissance Subgroup:

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Introduction:

To address fundamental scientific questions regarding the habitability and composition of Europa's subcrustal ocean, a landed spacecraft capable of *in situ* sampling and analysis represents a likely future step. To maximize success of such a landed mission, ensuring both safe landing and access to surface material of highest scientific value, some level of reconnaissance is necessary. Including a reconnaissance remote-sensing package on the next spacecraft mission to Europa (e.g., Europa multi-flyby "Clipper" or Orbiter) may present the most cost effective way of obtaining this needed data. To this end, the Science Definition Team was asked by NASA to "examine what datasets are required to lower the risk of landing on the surface of Europa", "understand what portion of those datasets could be provided with a precursor […] mission", and "examine how that data would be gathered and the impact to the mission concept."

The goals of obtaining reconnaissance data are twofold. The first goal is to provide information about the nature of the Europa surface from which to enable the design of a landed spacecraft, optimize a scientific payload, and develop a mission profile. The second goal of reconnaissance is to obtain sufficient information about the surface hazards and scientific characteristics at specific candidate landing sites from which NASA could later make the final selection of the landing-site. Inherent in these goals is maintaining adequate lead time prior to the landed mission's design, launch, and in-flight operation in order to conduct an appropriately-comprehensive scientific analysis of the reconnaissance data to support the surface mission. Without realizing both of these goals a landed mission will incur an unacceptably high risk.

The objective of this report is to summarize the findings of the 2012 Europa Clipper/Orbiter Science Definition Team's reconnaissance subgroup regarding the types of datasets that would be needed and the goals of obtaining these data, archetypal methods (types of observations and notional instruments) for obtaining these data, and the risks associated with not obtaining these data prior to launching a landed mission.

Underlying Assumptions:

This study assumes that the scientific objectives and the style of a landed mission follows that of the May 2012 lander mission report "Europa Study 2012 Report: Europa Lander Mission". This mission design included a soft lander carrying a scientific payload to address the habitability of Europa through *in situ* compositional and contextual analyses of the accessible surface layer. Direct sampling of the surface and near-surface material (ice, mineral, and organic) through drilling and delivery of samples to a suite of onboard analytical instruments was an integral component. This mission design set forth certain requirements for survivable slopes, acceptable scale of surface protrusions, and accessibility of scientifically compelling surface materials. These materials should be "geologically fresh" ices containing a natural sampling of mineral and (potentially) organic compounds, minimally degraded by physical, chemical, and space weathering processes.

We also assume that the information needed to sufficiently retire risk and make the decision to launch a lander would be obtained by a reconnaissance package on the Europa Clipper or Orbiter mission, in combination with the mission's existing scientific payload. A finding of the previous report [Europa Study Team, 2012] was that the lifetime of the lander's orbiting carrier and the time required to scout and certify a landing site were wholly incompatible, primarily due to the harsh radiation environment and short spacecraft life expectancy in Europa orbit.

Customers and Suppliers:

There are ultimately three customers for reconnaissance data and results: i) The engineering community (spacecraft and instrument teams) needing information about the surface environment from which to design a robust spacecraft, various subsystems, and the scientific instruments; ii) The science community needing structural, compositional, and geo-historical knowledge of the surface from which to analyze and down-select to optimal recommended landing sites, and to optimize the objectives of *in situ* experiments; and iii) NASA management needing to consider risk assessments and the desires of the science community to make a final site selection.

These reconnaissance results would be supplied by science-driven instrument teams (scientists and engineers) who would drive the design of instruments around reconnaissance and associated analysis requirements. These teams would then target the remote sensing instruments, acquire and validate the data, conduct initial analysis to produce preliminary characterizations of the surface, and as possible retarget and reprioritize data acquisition of various potential landing sites based on these initial findings to maximize the quality and value of collected reconnaissance data. This approach has been successfully applied to a myriad of landed missions to Mars [*e.g.,* Golombek *et al.,* 2003; Arvidson *et al.*, 2008; Spencer *et al.,* 2009; Grant *et al.,* 2010; Golombek *et al.,* 2012]. The objective of these instrument teams is to collect the best possible datasets and to leave final site characterization and evaluation as a future task for the combined science and engineering community.

Basis of Requirements:

In order for NASA ultimately to select a single landing site on Europa we anticipate that no less than two sufficiently low-risk and scientifically-compelling landing sites will need to be identified after elimination of unacceptable sites by analysis of reconnaissance data. Historical attrition rates of Mars potential landing sites suggest that approximately 1 in 10 sites will be certified as offering acceptable risk and appropriate science. Given the unknown basic nature of Europa's surface at the lander scale (relative to the volume of knowledge of Mars' surface), balanced by the absence of a substantial atmosphere and associated uncertainties, we estimate an attrition rate between 7:1 and 8:1 may be appropriate for down-selecting potential Europa landing sites. Therefore we estimate that at least 15 sites will need to be fully investigated (observed with a full complement of reconnaissance and science instruments) in order to certify at least two minimal-risk and scientifically-compelling site options for NASA. These sites should also represent a range of geological diversity in order to avoid lander-scale hazards that may pathologically occur for certain types of terrains. Investigating more than a minimum of 15 sites would be desirable given the current nearly complete lack of knowledge of surface structure or the geological and geophysical processes that mold the surface at the scale of a lander.

As noted above, we have assumed the basic lander design, capabilities to handle hazards, and the overarching scientific objectives of the landed mission. These capabilities include being able to stably land on slopes up to ~25 degrees on a three-meter baseline and manage surface obstacles (ice blocks, hard protrusions, and other roughness characteristics) extending up to one meter above the surface. Europa's surface is dominated by an unknown combination of tectonic, cryovolcanic, mechanical and space weathering, and sublimation processes with few strong Earth analogs. In addition to slopes and blocks, roughness elements may include scarps, steps, cracks, divots, cusps, and spires.

The scientific payload of the lander would address questions of habitability through drilling, sampling, and analysis. This payload would therefore require direct access to relatively pristine surface materials that may lie beneath a particulate and significantly altered regolith of unknown structure and thickness. While globally the surface of Europa is considered geologically young and the regolith developed through meteoric impact should be thin [Moore *et al.,* 2009], regional and local lander-scale variability is expected due to differences in surface age, redistribution of unconsolidated regolith, and sublimation/condensation/cementing of volatile ices.

To address these requirements and lower the risk to landing and operating on the surface, several key data sets are needed: i) mapped block abundance statistics for blocks greater than or equal to one meter in height; ii) mapped surface slopes characteristics on a three meter baseline; and iii) mapped hazardous surface-roughness elements on scales from sub-meter up to tens of meters. In addition to lowering the risk to surface drilling and sampling, knowledge of regolith physical characteristics of structure and thickness are also needed with emphasis on regolith consolidation, regolith thickness, and subsurface structure. Mapping properties such as regolith thickness in relation to observed landforms will allow for correlation of these properties with geologic processes and allow for extrapolation to smaller scales. All of these mapped data are needed over a region of the surface covering a scale larger than a potential landing ellipse in order to: i) conduct simulations of entry, descent, and landing to estimate probabilities of success; ii) adjust the ellipse location and orientation to minimize risk; iii) certify potential landing sites; and iv) provide onboard maps for the lander to perform terrain relative navigation.

Aside from being safe, a landing site must also be scientifically compelling. It must exhibit properties of composition, surface and resurfacing age, and geo-historical context to best offer an opportunity for sampling representative ocean or other subsurface liquid material. On a global scale, the surface of Europa is geologically young [Bierhaus *et al.,* 2009]. Fresh material may have been brought to the surface through a complex mixture of cryovolcanic, tectonic, and impact processes, where it would be subsequently chemically weathered by radiation, ion implantation, sublimation and condensation. Additionally, the surface is mechanically weathered by impact gardening and micrometeorite erosion, tectonics, mass wasting, sublimation and condensation, and sintering. Identification of a scientifically compelling site will require acquisition of compositional, geomorphological, and geophysical data.

Observations and Notional Instruments:

While in practice any and all available data is utilized collectively to characterize, evaluate, and certify potential landing sites and to design a landed mission, specific remote-sensing data types have proven the most essential in past missions. These types include high-resolution visible imaging, spectroscopic imaging, and thermal-infrared imaging. Additional datasets have also proven useful and complement these primary data and include radar-reflectivity and laser-altimetry mapping. Uses of these observations in addressing landing-site requirements are sometimes multifold. A traceability matrix that flows from reconnaissance goals, observation types, and notional instruments is provided in Foldout 1 (see attached).

For this study we have divided the observations into two classes. 1) Engineering: Support mission engineering, design, and site selection through analysis of landing site hazards related to obstacles and topography (Table I). 2) Scientific: Support landing-site characterization and selection through analysis of site composition, geomorphology, geophysical characteristics and geological history related to the science objectives of a landed mission (Table II). Each Table provides a ranking of the priority of the observations along with a risk assessment if such data are not acquired. Specific requirements and specifications for notional instruments are give in Foldout 1.

Table I. Observations for Lander Mission Engineering, Design, and Site Selection.

Priority	Observation	Purpose	Down-Select Risk
Very High	High-Resolution Imaging	• Map block abundance. • Characterize ≥ meter-scale surface roughness.	• Inability to assess landing hazards.
Very High	High-Resolution Stereo Imaging	• Map surface slopes for lander tilt hazard, terrain-relative navigation.	• Inadequate slope characterization. • No data to support active landing systems.
High	Thermal Infrared Imaging	• Verify visible block abundance & extrapolate to submeter scale. • Validate average surface roughness & extrapolate. • Identify regolith cover.	• Risk to interpretation of block abundance data. • Risk to evaluating lander footing and surface stability. • Risk to sampling mechanisms.

Table II. Observations for Scientific Site Evaluation, Certification, and Selection.

Priority	Observation	Purpose	Down-Select Risk
Very High	Spectroscopic Imaging	• Find sites of compositional interest for habitability studies. • Identify concentration and local variability, ocean representation, and recent extrusion.	• Inability to identify interesting sites for lander-based compositional science.
Very High	Context Imaging	• Identify context to global scale geologic processes • Identify sites of recent geologic activity, relation to subsurface extrusions and upwelling.	• Inability to identify geologic processes relative to ocean-surface exchange.
High	High-Resolution Imaging	• Characterize surface history in terms regolith development, bedrock and block physical weathering, surface age, and mass movement. • Identify bedrock exposures, regolith coverage.	• Limits knowledge of lander-scale surface material processing and weathering.
High	Thermal IR Imaging (Physical Properties)	• Identify block population and weathering processes. • Identify regolith characteristics, structure, heterogeneity, and thickness.	• Limits knowledge of regolith and bedrock of surface to be sampled by lander.
High	Sounding Radar	• Identify sites proximal to shallow liquid water and potential for recent extrusion of ocean material.	• Limits knowledge of potential relation between surface and current nearby liquid water
Medium	Stereo Imaging (Context and HiRes)	• Understand the relative uplift and subsidence processes that relate the site to subsurface exchange. • Characterize local slopes that drive mass movement and landform development.	• Limits interpretation of surface processes. • Limits knowledge of mass wasting processes.
Low	Thermal IR Imaging (Thermal Anomaly)	• Identify sites of current or recent extrusion through anomalously high temperatures.	• Limits discovery of hot spots.

High Resolution Imaging – High-resolution visible imaging is needed for a variety of purposes from block-hazard identification, to identifying surface-roughness elements, slope movement, regolith variations, and bedrock exposures. In addition, high resolution is needed to understand lander-scale and landing-ellipse-scale geologic variability, surface age and resurfacing history, resurfacing mechanisms, and physical weathering processes.

Context Imaging – In order to understand the relationship between high-resolution imaging and the regional-scale and global-scale geologic history, context imaging is needed to bridge resolution gaps. Depending on the terrain, resolution steps of at most 10x or smaller are needed to meaningfully transition between image resolutions, such at that the highest resolution is supported by ten times coarser resolution imagery for context with a broader field of view and so on until the regional or global scale context is sufficiently understood.

Stereo Imaging – High-resolution stereo imaging is necessary to characterize surface slopes as a landing hazard. In addition, stereo data is valuable in understanding regolith movement (slope stability) and cohesion, tectonic uplift and subsidence, cryovolcanic flow thickness, and surface degradation rates relative to impact rates and surface age. Stereo-pair observations require similar lighting conditions (if not the same), necessitating paired images on the same flyby pass or careful timing and alignment of orbital passes.

Thermal Infrared Imaging – Observations of the brightness temperature of the surface can be used in a variety of ways to estimate regolith particle cohesion, block abundance, and bedrock exposures. Observations at more that one time during an orbital cycle (*i.e.*, diurnal rotation) can additionally aid in interpreting regolith thickness and subsurface cohesion. In addition, thermal-infrared imaging can be used to locate potential "hot spots," sites of recent or active exposure of warm subsurface or oceanic material.

Spectroscopic Imaging – Determination of mineral and potential organic components present on the surface (location and concentration) is a key element of meeting the science objectives of a landed mission intended to sample and analyze these materials. In addition, understanding the spatial variability of composition and the correlation of this variability with various landforms and geological processes will aid greatly in extrapolating compositional information to lander scales.

Sounding Radar – Subsurface detection of shallow liquid water would raise the likelihood that surface materials may have recently cryo-volcanically extruded or been tectonically uplifted. Used in conjunction with high-resolution and context imaging these data would help clarify the resurfacing history at lander and ellipse scales.

Additional New and Existing Data – Other types of data, if available, can be used to support and corroborate the interpretation of surface properties from primary observations noted above. These data are not considered required, but can offer some cross-checking of interpretations of primary data sets. These include RMS-slope parameterization obtained from the surface return along the nadir track of the subsurface sounding radar, laser altimetry from which long baseline slopes can be compared with short baseline stereo, and laser shot dispersion which provides some information about overall surface roughness. While existing data from past missions are on a whole inadequate in spatial resolution to characterize landing sites, these data provide additional global-scale geological context (visible imaging), constraints on regional-scale surface structure (thermal emission), and limited regional compositional information (spectroscopy).

Notional instruments to obtain reconnaissance observations outlined in Tables I and II (along with relative priorities) are listed in Table III. Detailed requirements and objectives are listed in the traceability matrix (Foldout 1).

Table III. Notional Instruments and Accommodation.

Notional Instrument	Engineering Priority	Science Priority	Clipper Accommodation	Enhanced Orbiter Accommodation
High Resolution Imager	Very High	High	Yes	Yes
High Resolution Stereo Imager	Very High	Medium	Yes	Yes
Thermal Infrared Imager	High	High	Yes	no
Spectroscopic Imager	n/a	Very High	Yes	no
Context Imager	n/a	Very High	Yes	no
Sounding Radar	n/a	High	Yes	Yes
Context Imager Stereo	n/a	Medium	Yes	no

Operational Scenarios and Constraints:

We explicitly assumed that the follow-on activity of landing-site characterization, evaluation, and selection using the returned reconnaissance data are not part of either Orbiter or Clipper mission designs. These data will be used later by the science community to evaluate landing sites and make recommendations toward a future landed mission. Thus, thoughtful and appropriate collection of reconnaissance data is essential.

Data Evaluation - Initial data evaluation/validation and preliminary analyses are needed for two reasons. The first reason is to ensure that quality and complete data sets are collected, free of corruption, gaps, and artifacts that might render the data for a particular site invalid or of limited utility. The second reason is to determine if retargeting is needed to either enhance coverage of a particularly compelling site, or to avoid expending valuable resources on pathologically non-survivable types of terrains.

Retargeting - Interwoven with these requirements is the ability to retarget reconnaissance coverage. Within the limits of Clipper or Orbiter mission designs, retargeting may be accomplished through small trajectory adjustments, existing repeat over-flights, or data-acquisition timing adjustments during flybys.

Multi-Observation Coverage – To properly evaluate the potential landing sites, each site will need a complete complement of the primary (high priority) observations. This can be accomplished through either multiple over-flight passes over the same site or careful coordination among instruments on a single over flight.

Traceability – Specific observations, notional instruments and quantitative constrains are given in the attached traceability matrix (Foldout 1).

Time of Day Constraints - Most data types require daytime illumination of the target area. As is typical of such missions, the optimal (sweet spot) time of day is not the same but acceptable ranges generally overlap. Additionally, coverage by thermal infrared observations during multiple times of day and night would aid in interpreting regolith properties and structures.

Summary:

Based on the assessment of a Europa lander concept [Europa Study Team, 2012], it became abundantly clear that the data to both design a robust landing system and to safely achieve the surface of Europa are not in hand. For this reason, it is important that the next mission to Europa have the capability to perform landing-site reconnaissance. The types of observations and notional instruments described here provide a blueprint from which the necessary data sets can be acquired.

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